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The focus of this project was the transition from a coherent—thus integrable and predictable— behavior to a thermal one in atom waveguides and optical lattices. The approach to the theme ranged from a purely pragmatic to a thoroughly fundamental. Over the years, the focus was gradually shifting from a loss of coherence toward a broader question of predictability of the outcome of a quantum device. We paied a special attention to the systems with additional conserved or quasi-conserved quantities, serving, in this context, as additional predictors.

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Final Technical Report

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FINAL TECHNICAL REPORT

Coherence Properties of Strongly Interacting Atomic Vapors in Waveguides

Maxim Olchanyi

Summary

The focus of this project was the transition from a coherent—thus integrable and predictable—behavior to a thermal one in atom waveguides and optical lattices. The approach to the theme ranged from a purely pragmatic to a thoroughly fundamental. Over the years, the focus was gradually shifting from a loss of coherence toward a broader question of predictability of the outcome of a quantum device. We payed a special attention to the systems with additional conserved or quasi-conserved quantities, serving, in this context, as additional predictors.

Results from N00014-06-1-0455 and N00014-09-1-0502

Atom beam-splitting in strongly interacting gases

An output of an atom beamsplitter is the simplest nontrivial far-from-equililibrium initial state of an atomic sample. The result of a consequent time propagation is determined by a competition between the conserved quantities of the non-interacting counterpart and the interactions between the atoms. Generally, the former tend to preserve coherence and the later lead to a thermalization of the sample and an inevitable decoherence. In this regard, the one-dimensional hard-core bosons [7-9, 24, 26-29] constitute a conceptually important intermediate case. On one hand, the free-fermionic integrals of motion tend to preserve the multi-beam structure of the atomic state and the coherence between the beams. On the other hand, the Bose-Fermi correspondence does not preserve the momentum distribution exactly. As a result, the beam-splitter peaks tend to broaden in the beginning, but the broadening stops well before the peaks start to overlap.

Another system we studied was a one-dimensional Bose gas on a lattice in the mean-field regime [22]. There the goal was to repeat, for our system, the Chirikiov-Izrailev program for Fermi-Pasta-Ulam chain and determine the position of the chaos/decoherence threshold. We found that while the threshold remains finite in the thermodynamic limit, it moves towards infinite densities in the continuum limit. In particular this means that interaction-induced dynamical chaos does not seem to constitute an obstacle for a coherent operation of a beamsplitter.

Influence of the conserved and quasi-conserved quantities on the output of a quantum device

If a system possesses some nontrivial integrals of motion, the final state of the system after a time propagation will remember their initial values. However, even when the number of the conserved quantities (in involution) is as high as the number of the degrees of freedom, still, only a half of the phase coordinates is predictable: the corresponding canonical angles will be uniformly (in case of incommensurate frequences) covering the remaining submanifold. By analogy with a conventional microcanonical ensemble, one may devise an ensemble where not only the energy, but other integral of motion as well are bounded by respective windows. Such a statistical model will have a much higher predictive power than the standard thermodynamics.

A canonical version of the generalized microcanonical ensemble above (the so-called Generalized Gibbs Ensemble) has been proven to be operationally simple highly accurate theory for an outcome of the time evolution of a gas of impenetrable bosons [5, 7, 9, 24, 26-29]. On the other end of the integrability-ergodicity continuum, the memory of the initial conditions vanishes for all initial states: quantitatively, this manifests itself in the eigenstate-to-eigenstate variance becoming much smaller [1, 2] than the quantum fluctuations. This effect is called Eigenstate Thermalization. We have successfully demonstrated the effect for the cases of a two-dimensional lattice with hard-core bosons [3, 4, 6, 11, 23], a one-dimensional lattice with hard-core bosons interacting via a soft-core and, in a different realization, via a three-body potential [1, 2], and a Josephson junction with two species of bosons [21].

We payed a special attention to the transition between the integrable and ergodic regimes. We found that in the cases of a rough quantum billiard [14] and in two atoms in a harmonic waveguide [16, 17, 20, 21] (constituting a Šeba billiard), there exists a closed form analytic description of the correlation between the final and initial values of an observable that covers the full range of parameters from the integrable regime through a fully developed quantum chaos.

To treat the fluctuations of the expectation values of observables across the spectrum (that define a typical deviation from ergodicity), we introduce a geometric structure—based on the

Frobenius or Hilbert-Schmidt inner product—to the space of quantum observables [1, 2]. The induced measure allows one to identify the most relevant information about the initial state needed to accurately predict the outcome. We envision that this technique can be successfully applied for design of quantum mesoscopic devices.

Exotic symmetries in cold gases: supersymmetry, dynamical symmetry, and quantum anomalies

We performed an extensive study of the relationship between some cold-gases-relevant PDEs (Nonlinear Schrödinger (NLS) (bosonic waveguide) and sine-Gordon (sG) (two coupled bosonic or fermionic waveguides)) and the Quantum-Mechanical Supersymmetry (QM-SUSY) [15]. We found that the QM-SUSY emerges in two unrelated instances: a property of the first Lax operator and the Bogoliubov-de-Gennes (BdG) Liouvillian respectively. In the first case, the QM-SUSY removes the thermal noise around multi-solitonic solutions. In the second case, the QM-SUSY guarantees that the BdG propagation correctly describes a penetration of a small soliton(breather) through a large stationary soliton of the NLS(sG) equation.

Next, we predicted and subsequently studied the quantum-mechanical symmetry breaking or quantum anomaly for the Pitevskii-Rosch dynamical symmetry (decoupling of the monopole motion for two-dimensional harmonically trapped Bose gases). We obtain an expicit expression for the anomalous shift in the monopole frequency and provided concrete suggestions for an experimental observation of the effect [19]. In our opinion, the monopole shift constitutes another macroscopic predictor for the (microscopic) equation of state, complementary to the density profile.

Publications under N00014-06-1-0455 and N00014-09-1-0502

invited conference presentations

[1] **Quantum Integrability versus Quantum Thermalizability** (full lecture course), Summer School on "Quantum Many-Body Physics of ultra-Cold Atoms and Molecules" Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, July 2-13, 2012 (forthcoming)

[2] **Quantum Integrability versus Quantum Thermalizability**, APS March Meeting, Boston, MA, Feb 27 - Mar 2, 2012

[3] **The Eigenstate Thermalization Hypothesis and Quantum Thermodynamics**, Summer College on "Nonequilibrium Physics from Classical to Quantum Low Dimensional Systems", Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, July 6-24, 2009

[4] **The Eigenstate Thermalization Hypothesis and Quantum Thermodynamics**, APS March Meeting, Pittsburgh, PA March 16-20, 2009

[5] **Quasi-Thermodynamics of Isolated Integrable Quantum Many-Body Systems**, ITAMP workshop on "Non-equilibrium Dynamics and Correlations in Strongly Interacting Atomic, Optical and Solid State Systems", Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA, January 26-28, 2009

[6] **The Eigenstate Thermalization Hypothesis and Quantum Thermodynamics**, Joint fall meeting of the New England Sections of the APS and AAPT, Boston, MA, October 10-11, 2008

[7] **Empirical manifestations of integrability in cold quantum gases**, Joint Physics/Mathematics Workshop on Quantum few-body Systems, Aarhus, Denmark, March 19-20, 2007

[8] **Exact properties of strongly correlated ultracold gases in tight waveguides**, International Conference on "Laser Physics", Lausanne, 24-28 July 2006 [subcontracted under N00014-06-1-0455]

[9] **Empirical manifestations of integrability in cold quantum gases**, 37th Meeting of the Division of Atomic, Molecular and Optical Physics Knoxville, TN, May 16-20, 2006

books, invited reviews, editorials, etc

[10] Maxim Olshanii, **Quantum Mechanics in Two Lines: Qualitative Methods in Linear and Nonlinear Quantum Mechanics** (book, contracted) (World Scientific (2012))

[11] Vanja Dunjko and Maxim Olshanii, **Thermalization in isolated quantum systems** (invited review, contracted), Annual Review on Cold Atoms (World Scientific (2012))

[12] Vanja Dunjko, Michel Moore, Thomas Bergeman, and Maxim Olshanii, **Confinement-induced resonances** (invited review), Advances in Atomic, Molecular, and Optical Physics, 60, 461 (2011)

[13] V. A. Yurovsky, M. A. Olshanii, D. S. Weiss, **Collisions, Correlations, and Integrability in Atom Waveguides**, Advances in Atomic Molecular and Optical Physics, **55**, 62 (2008)

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[14] Maxim Olshanii, Kurt Jacobs, Marcos Rigol, Vanja Dunjko, Harry Kennard, and Vladimir Yurovsky, **An exactly solvable model for the integrability-chaos transition in rough quantum billiards**, Nature Communications **3**, 641 (2011)

[15] Andrew Koller and Maxim Olshanii **Supersymmetric Quantum Mechanics and Solitons of the sine-Gordon and Nonlinear Schrdinger Equations**, Phys. Rev. E **84**, 066601 (2011)

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